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19. ABSTRACT (Continue on reverse if necessary and identify by block number) In Task I an experimental study of the ignition of Jet-A fuel sprays by an isothermal hot surface was conducted in a vertical axisymmetric duct. The ranges of flow conditions under which ignition was investigated were: <table border="0"> <tr> <td>Free stream velocity</td> <td>1 to 5 m/sec</td> </tr> <tr> <td>Momentum thickness of the b.l.</td> <td>3 to 20 mm</td> </tr> <tr> <td>Free-stream air temperature</td> <td>40 to 250 C</td> </tr> <tr> <td>Fuel concentration</td> <td>Ignitability limits</td> </tr> <tr> <td>Droplet size (SMD)</td> <td>20 to 200 microns</td> </tr> </table> In addition to measurements of the wall temperature necessary for ignition, under the above conditions, local measurements of velocity, turbulence intensity, fuel concentration, and the fraction of fuel vaporized were measured in the boundary layer at surface temperatures just below that required for ignition. The results exhibited vapor ignition trends						Free stream velocity	1 to 5 m/sec	Momentum thickness of the b.l.	3 to 20 mm	Free-stream air temperature	40 to 250 C	Fuel concentration	Ignitability limits	Droplet size (SMD)	20 to 200 microns
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Task I (continued)

for most of the flow conditions, with some exceptions where single droplet ignition appeared to be present. The experimental data were found to be in agreement with existing vapor ignition theory for the ranges of conditions studied.

In Task II two combustion tunnel facilities were used to investigate the stabilization of aircraft fires. The largest of these has two rectangular test sections, 0.15 x 0.2 m, and 0.3 x 0.3 m. Vee-gutter flameholders with included angles from 30° to 180° and widths to 10 cm were tested, with the usual orientation of the gutters. Tests were also conducted with a flat plate mounted normal to the top of the test section to create a single-vortex flow pattern. Velocities from 30 to 200 m/sec, temperatures from 373 K to 565 K, and effective pressures from 4.2 to 35.2 kPa were employed in the tests. Stability characteristics were assessed using the well-established water injection technique. The results obtained showed that the shape of a bluff-body flameholder affects its stability characteristics through its influence on the size and shape of the wake region. Another significant finding was that the flameholding properties of the single-vortex flow pattern are markedly superior to those of the double-vortex pattern.

The extensive experimental results on blowoff velocity, obtained using both conventional Vee-gutter and single sided flameholders, provided the data base for an analytical study of the factors governing the stability characteristics of bluff-body flameholders. An equation was derived for predicting blowoff velocity in terms of flameholder size, flameholder blockage, ambient air pressure and temperature, and laminar flame speed. Predictions of blowoff velocity based on this equation showed excellent agreement with the experimental values obtained in this investigation and with the published results of other workers. The measurements of blowoff velocity obtained for both gaseous and liquid fuels, generally confirmed theoretical predictions in regard to the dependence of peak blowoff velocity on laminar flame speed. They also showed that gas turbine fuels in the range from Jet A to diesel oil (DF2) exhibit very similar flameholding characteristics, since their laminar flame speeds are virtually the same.

A series of tests carried out on flameholders of irregular shape showed that any irregularity in the shape of a bluff body tends to diminish its stability. The results indicate that the most effective flameholder is one that produces a wake region having the minimum surface area to volume ratio.

In Task III experimental studies have been conducted on the following: (1) Entrainment of an external flow into a cavity, with a small opening or vent in a side wall, when there is a small flow through the cavity; and (2) Fluid dynamics and ignition and flame stability characteristics of a jet of gaseous fuel through a protrusion of different shapes and heights in the wall of a cavity with a small flow of air through the cavity. Flow and flame visualization have been utilized for determining the flow and flame characteristics. Locations where ignition is feasible and lean limits for ignition have been established. Based on an analytical model, the turbulent, inert and reactive, flowfields have been predicted utilizing a three-dimensional reactive flow prediction code. The predictions, generally more satisfactory in the region downstream of the protrusion, confirm the importance of residence time and mixture ratio in vorticity-concentration regions, shear levels and recirculation zones, attached or submerged, in ignition, flame location and flame stability. These findings are of relevance in cavity fires and design of blocker-type injectors for gas turbines and ramjets.

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FOREWORD

This final report is submitted by the Combustion Laboratory of the Thermal Sciences and Propulsion Center, School of Mechanical Engineering, Purdue University. The report documents work conducted under Air Force Contract/Grant No. AF 820107 during the period 15 November 1981 to 31 March 1986. Program sponsorship was provided by the Air Force Office of Scientific Research /NA under the guidance of Dr. Julian Tishkoff.

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Task I

IGNITION OF FUEL SPRAYS BY HOT SURFACES

J.G. Skifstad

Phase I. Ignition of Fuel Sprays by Hot Surfaces (J.G. Skifstad)

This experimental investigation was undertaken to explore the nature of fuel spray/air ignition by hot surfaces. The problem considered may be viewed as that of a uniform fuel spray/air mixture in a prepared momentum boundary layer encountering a step change in the wall temperature. The thermal boundary layer grows along the heated surface and preignition reactions occur in a region near the wall. Ignition of the fuel vapor in the boundary layer will occur if conditions are such as to support the growth of a suitable ignition kernel. For fuel spray/air mixtures, ignition can also occur in the fuel vapor/air mixture surrounding an individual droplet in the boundary layer flow. In that case the burning mixture can be transported with the droplet, which may or may not remain in the boundary layer. The experiments were conducted with Jet-A fuel and also with gaseous propane. Propane was selected to make a connection between the data obtained with the new apparatus and data in the literature and because propane and kerosine exhibit similar ignition behavior.

The experimental apparatus designed for the study had provisions for creating suitable flow conditions and for making measurements in the boundary layer under conditions approaching ignition. The ranges of flow conditions under which ignition was investigated were:

Free stream velocity	1 to 5 m/s
Momentum thickness of the b.l.	3 to 20 mm
Free-stream air temperature	40 to 250 C
Fuel concentration	Ignitability limits
Droplet size (SMD)	20 to 200 microns

The design of the system was such that those parameters could be varied independently. The temperature of the isothermal wall when ignition events occurred was determined for the range of conditions given. Local measurements of velocity, "turbulence" intensity, fuel concentration, and the fraction of fuel vaporized were made in the boundary layer at surface temperatures just below that required for ignition.

The hot surface in the experimental apparatus was the inner wall of an axisymmetric duct oriented vertically with the flow upward. The fuel spray was injected into a suitably prepared air flow in a manner such that the air flow was not greatly disturbed. In determining the temperature of the heated wall at which ignition occurred, the flow conditions were first established and the temperature of the heated wall was raised slowly (0.5 deg. C/sec) until ignition was observed. Ignition events were detected both by means of a photodiode and by visual observations. All ignition data reported corresponded to events leading to development of a flame consuming the entire combustible mixture. Ignition results were not found to be sensitive to the precise rate of heating of the wall.

It is useful to note that for virtually all of the runs made in this investigation, the fuel in the boundary layer was in the form of vapor. Under some conditions, however, a few large droplets evidently penetrated the boundary layer and impacted on the wall, as could be detected by a diminution of the local luminosity of the wall. And for conditions near the lean limit, ignition of the combustible mixture in the vicinity of individual droplets was observed. Except for the effects of the spray in cooling the outer portions of the boundary layer by evaporation and in contributing to the range of equivalence ratio present in the boundary layer, the situation would be expected to bear a close resemblance to the ignition

of gaseous fuel/air mixtures.

The surface materials employed in the study were stainless steel and pure nickel. Sections of 2-inch Schedule 40 pipe (5.08 cm i.d., 4.75 mm wall, 15.25 cm long) were utilized. The relatively thick wall served both to help minimize streamwise temperature variations of the wall temperature and to reduce the coupling of gas-phase thermal transients in the growth of an ignition kernel with local thermal transients in the wall properties. Seven thermocouples situated close to the inner surface at positions distributed along the duct served to monitor the wall temperature. The duct was heated by means of two, 2-kw CALROD units wrapped on its outer surface, and the entire assembly was insulated. The nickel surface exhibited serious oxidation under fuel-rich conditions, and it was accordingly difficult to obtain data representative of a clean nickel surface. The oxide coating generally tended to increase the wall temperature at ignition, and also tended to render erratic results for similar run conditions. While no intensive effort was made to determine contributions of heterogeneous reactions to those results, those observations seemed to be attributable to the insulating effect of the oxide flakes formed. The stainless steel also oxidized, but with a less severe effect on the ignition results.

Several velocity profiles were employed in the investigations reported. A "uniform" profile was established for most of the run conditions with propane, such that the velocity variation across the flow was within a few percent of being constant to within a few mm from the wall of the duct; the boundary layer thickness at the exit plane of the test section was about 5 mm.. To represent thicker boundary layers, at the start of the heated section the flow conditioning was arranged to provide a flow with a radial distribution peaked at the center, termed a "developed" profile. The ratio of the peak velocity to the bulk velocity for the "developed" profile increased roughly linearly with bulk velocity, to a maximum value of about 1.6 at a bulk velocity of 3.3 m/sec. The boundary layer thickness measured for the "developed" profiles at the exit of the test section, however, remained nearly the same for the ranges of bulk velocity considered. The boundary layers studied were predominantly laminar ones, subject to some level of "turbulence" in the free-stream core of the flow.

The principal evidence yielded by the experiments may be summarized as follows.

- 1) The surface temperature necessary for ignition decreased with increasing thickness of the momentum boundary layer at the start of the heated surface.
- 2) The surface temperature necessary for ignition increased with increasing free-stream velocity.
- 3) The surface temperature for ignition was lowest under stoichiometric bulk mixture conditions and increased for off-stoichiometric bulk compositions, as has been observed in ordinary fuel ignition studies.
- 4) Wide ranges of droplet sizes had little effect on fuel ignition; that could be attributed partly to the fact that under the flow conditions of interest here, virtually all of the fuel in the boundary layer was vaporized.
- 5) Increasing the temperature of the bulk mixture lowered the wall temperature required for ignition.

6) Both qualitative and quantitative evidence supported the inference that the thermal effect of vaporization of the fuel in the boundary layer was a significant factor in the ignition of a fuel spray, apart from the role of vaporization in merely establishing a combustible fuel/air spray.

7) A qualitative argument describing the ignition process in terms of the spontaneous ignition temperature of the fuel vapor and the thermal boundary layer thickness could adequately represent the general behavior of the ignition process for virtually all of the runs made in this study, supporting the conclusion that the thermal boundary layer thickness plays a dominant role in the problem.

While the experimental evidence is qualitatively consistent with simplified models of vapor ignition in a boundary layer flow, the influence of the transport of fuel to the boundary layer region via droplet motion remains to be investigated analytically, but could be expected to be prominent importance in the problem. The evidence gathered in these experiments is being employed to make some assessment of those effects by employing the modified CONCHAS-SPRAY code

Reports and Publications

1. Skifstad, J.G., et al., "Ignition of Fuel Sprays by Hot Surfaces and Stabilization of Aircraft Fires," AFOSR TR-79-0079 (ADA065153) November, 1978.
2. Graves, C.B., Tang, Y.L., and Skifstad, J.G., "Ignition of a Fuel Spray by a Hot Surface," AIAA Paper 85-1318, AIAA/SAE/ASME 21st Joint Propulsion Conference, Monterey, CA, July, 1985.
3. Graves, C.B., Tang, Y.L., and Skifstad, J.G., "Experimental Apparatus for Studying the Ignition of a Fuel Spray by a Hot Surface". AIAA Paper 85-1317, AIAA/SAE/ASME 21st Joint Propulsion Conference, Monterey, CA, July, 1985.
4. Graves, C.B., Tang, Y.L., and Skifstad, J.G., "Ignition of a Fuel Spray by a Hot Surface," article to be published in the AIAA Journal, fall, 1986.
5. Skifstad, J.G., "An Automated Imaging-Type Spray Analysis System for Local Spray Properties" presented at the ICLASS-82 meeting in Madison, WI, 1982.
6. Skifstad, J.G., "Microscopic Airblast Atomizers" presented at the ICLASS-82 meeting in Madison, WI, 1982.

Advanced Degrees

1. Kelly, M.S., "Probe System for Composition Measurement of Fuel Spray/Air Mixtures," M.S. Thesis, School of Mechanical Engineering, Purdue University, W. Lafayette, IN 47907 (1983).
2. Sacksteder, K.R., "A Laser Doppler Anemometer for Measurements in Fuel Sprays," M.S. Thesis, School of Mechanical Engineering, Purdue University, W. Lafayette, IN 47906 (1982).
3. Graves, C.B., "Spray Ignition by a Hot Surface". M.S. Thesis, School of Mechanical Engineering, Purdue University, W. Lafayette, IN 47907 (1984)
4. Tang, Y.L., "Numerical Investigation of Fuel Spray Ignition by a Hot Surface," Ph.D. Thesis, School of Mechanical Engineering, Purdue University, W. Lafayette, IN 47907 (in preparation).

Task II

STABILIZATION OF AIRCRAFT FIRES

A.H. Lefebvre

TASK II - SUMMARY

1. Reporting Period: 5/81 thru 3/31/86
2. Starting Date: 11/15/81
3. Objectives: To investigate the flame stabilization characteristics of flameholders of large size and irregular shape, and to derive theoretical relationships for blowoff velocity in terms of ambient pressure, temperature, flameholder size and flameholder shape. Also to investigate the influence of fuel type on flameholding characteristics.
4. Relevance: The results obtained in this study enable conditions to be prescribed under which regions of separated flow on an airframe could stabilize a flame. These results cover all fuels of interest to the Air Force in the foreseeable future.
5. Principal Finding: The most important outcome of the research was the derivation of an equation, supported by experimental data, for predicting the blowoff velocity of a stabilized flame in terms of flameholder size, flameholder shape, and ambient air conditions. This equation can be used to predict the minimum size of airframe structural protrusion needed to stabilize a flame for any stipulated conditions of aircraft flight speed and altitude.
6. Publications: The work has resulted in four journal publications (refs. 3 thru 6) and two ASME awards.
7. Interactions: The equation derived for blowoff velocity is directly applicable to the design of flameholders for afterburners and ramjet systems.
8. Personnel: The key people employed on this program, in addition to the principal investigator (A.H. Lefebvre) were Visiting Scholars Dr. K.V.L. Rao (now Deputy Director of the National Aeronautical Laboratory in Bangalore, India) and Dr. N.K. Rizk (now in the Combustion Department of Allison Gas Turbines), and graduate student R.M. Stwalley.

Introduction

One objective of the research was to extend the range of experimental data on the stabilization properties of bluff-body flameholders to include flameholders of large size (characteristic dimension up to 10 cm) and irregular shape, such as might arise on the external surface of an aircraft due to structural damage. Another goal was to derive suitable theoretical relationships for blowoff velocity for the extended range of flame holder sizes and shapes.

The stabilizing performance of a bluff-body flameholder is usually described either in terms of the range of equivalence ratios over which stable combustion can be achieved, or by the maximum flow velocity that the system can tolerate before flame extinction occurs. Both aspects are important in practical combustion systems. In a prior study sponsored by the U.S. Air Force Ballal and Lefebvre [1,2] investigated in detail the factors that govern the lean blowoff limits of bluff-body stabilized flames supplied either with homogeneous combustible mixtures or with heterogeneous mixtures of fuel drops of air. Their model for the mechanism of lean blowoff provides very satisfactory correlation of their experimental data as well as the results obtained by other workers [3]. Unfortunately, the model is valid only for equivalence ratios below around 0.7. This limitation led to the development of a further model for predicting peak blowoff velocities which usually occur at or near the stoichiometric fuel/air ratio [3].

Due to apparatus limitations, in particular the difficulty and high cost of providing high air flow rates at low (subatmospheric) pressures, most of the previous work on bluff-body flame stabilization has utilized fan air. This is essentially at atmospheric pressure, so that where the flameholders tested have been of a practical size, the results have usually been confined to very weak or very rich mixtures. Where tests have been carried out in the most interesting fuel/air ratio range, i.e., near stoichiometric, either velocities have been very high or dimensions very small. In either event extrapolation to practical velocities or practical dimensions has been a somewhat dubious process. It is difficult to extrapolate dimensions because any such extrapolation must also take into account effects arising from a change in "blockage". It is equally difficult to extrapolate velocities because at high velocities compressibility effects can change the flow pattern in and around the combustion zone.

In this investigation these problems were surmounted using the well-established "water injection technique" in which low pressures are simulated by injecting water or steam into the fuel-air mixture flowing into the combustion zone. This approach allows complete stability loops to be drawn for large flameholders, up to 10 cm in effective width, at simulated pressures down to one-twentieth of an atmosphere.

Experimental

The main advantage of the water injection technique is that it allows the combustion performance of large-scale combustion systems to be fully evaluated while operating within their normal range of velocities and fuel/air ratios. Air is supplied at normal atmospheric pressure, usually from a fan, and lower pressures are simulated by introducing water into the combustion zone. The success of the method relies on the inability of the reaction zone to detect the difference between a reduction in gas pressure and a reduction in reaction temperature which, in this instance, is accomplished by the addition of water.

The apparatus employed comprises a supply of air at atmospheric pressure, a preheat combustion chamber, a working section containing the flameholder under test, and provision for injecting kerosine and water in well-atomized form into the flowing gas upstream of the flameholder. Sufficient time and temperature is provided between the planes of injection of water and kerosine and the flameholder to ensure that both liquids are fully prevaporized and premixed upstream of the reaction zone.

The test procedure is quite simple. The velocity and temperature of the gas flowing over the stabilizer are adjusted to the desired values; the fuel is turned on and a flame established in the recirculation zone downstream of the stabilizer. Water is then gradually admixed with the kerosine in increasing amounts until extinction occurs. This process is repeated at a sufficient number of fuel flow rates for a complete stability loop to be drawn.

Curves of this type provide a useful means for comparing the basic stability of various designs of flameholder. The value of the technique is greatly enhanced by the relationship which has been derived from global reaction rate considerations between the amount of water added and the equivalent reduction in gas pressure. In general, it is found that injecting into the combustion zone a quantity of water equal to the kerosine flow rate is equivalent to halving the gas pressure.

Two rectangular test sections, size 0.15 x 0.2m and 0.3 x 0.3m, were employed in order to separate the effects of flameholder size from those of flameholder blockage. Several Vee-gutter flameholders were constructed with included angles of 30, 45, 60, 90, and 180 deg. Normally the flameholder was mounted vertically at the center of the test section with its apex pointing upstream. However, one series of tests was conducted with a 180 deg gutter (i.e., a flat plate) fitted to the top of the test section. The purpose of this arrangement was to produce a single-vortex flow pattern in the flameholder wake instead of the usual double-vortex formation.

Further tests were carried out on flameholders of irregular shape, such as might arise on the external surface of an aircraft due to structural damage. The flameholders selected for this study were six Vee-shape gutters manufactured to the same length (14 cm) and the same trailing edge width of 7.6 cm. They ranged in included angle from 30° to 180° in steps of 30°. After measuring the pressure loss and stability characteristics of all six gutters, four rectangular strips of material were removed from both sides of each gutter. These strips were 0.64 cm wide and they extended from the trailing edge to halfway back toward the nose. Subsequent cuts were then made, in steps of 0.64 cm, until finally the flameholder was restored to its original plain-Vee shape, but having half its original width. For all configurations measurements were made of pressure loss, aerodynamic blockage, and stability performance, the latter using the water injection technique, as described below.

The experimental program covered the following ranges of velocity, temperature, and effective pressure as measured in the gases just upstream of the flameholder.

Velocity 30-220 m/s

Temperature 373-565 K

Effective pressure 4.2-35.2 kPa

Theoretical Aspects

From considerations of the residence time and chemical reaction time in the wake region of a bluff-body stabilized flames, it is concluded that the influence of operating conditions and flameholder size, geometry, and blockage is adequately described by the following equation for blowoff velocity.

$$U_{BO}/S_L = C_s(1 - B_a) \text{Re} \text{Pr} \quad (1)$$

where U_{BO} = blow-off velocity
 S_L = laminar flame speed
 C_s = flameholder shape factor ($=B_a/B_g$)
 B_a = aerodynamic blockage of flameholder
 B_g = geometric blockage of flameholder
 Pr = Prandtl number
 Re = Reynolds number $= (S_L D_c \rho_o / \mu_o)$
 D_c = characteristic dimension of flameholder

An alternative form of Eq. (1), which serves to demonstrate that blowoff velocity is proportional to the square of laminar flame speed, is the following.

$$U_{BO} = C_s (1 - B_a) (D_c S_L^2 / \alpha_o) \quad (2)$$

Equations (1) and (2) were found to predict not only the experimental values of blowoff velocity obtained in this AFOSR research program, but also the results obtained by other workers.

The influence of fuel type on flame stability was also examined. From inspection of Eqs. (1) and (2) it is clear that the only way in which a change in fuel type can affect blowoff velocity is via the laminar flame speed, S_L . However, most hydrocarbon fuel-air mixtures tend to have very similar values of S_L , usually in the range between 0.35 and 0.43 m/s. Thus, according to Eqs. (1) and (2) only slight variations should be observed in the stability limits for gasoline (JP 4), kerosine (Jet A) and diesel oil (DF2), which had been chosen to represent the range of fuel types likely to be encountered in aircraft jet engines in the foreseeable future.

It was found that the stability loops for gasoline, kerosine and diesel oil are practically the same. The slight observed differences between these fuels is attributed to differences in their latent and sensible heat requirements, which cause the vapor-air mixture for gasoline to be higher than that of kerosine which, in turn, is higher than that of diesel oil. The practical significance of this result is that the threat to aircraft safety from external fires stabilized either by structural protrusions or regions of separated flow on the airframe, is virtually the same for a relatively low volatility fuel, such as diesel oil (DF2) as it is for a fuel of higher volatility, such as JP 4.

A considerable number of measurements of blowoff velocity were carried out on flameholders of irregular shape. Detailed measurements of static pressure were carried out both in and around the flameholder region, in order to establish relationships between flameholder pressure drop, flameholder size, shape, aerodynamic drag, and blowoff velocity. It was found that for any given flameholder size and blockage, the introduction of any irregularity in flameholder shape tends to reduce the flame stability. In general the most effective flameholder is one that produces a wake region having the minimum surface to volume ratio.

Main Accomplishments

1. Equations have been derived for predicting the blowoff velocity of bluff-body stabilized flames in terms of fuel type, ambient air pressure and temperature, flameholder size and flameholder geometry.
2. It has been demonstrated both theoretically and experimentally that the threat to aircraft safety from external fires, stabilized either by structural protrusions or regions of separated flow on the airframe, is virtually the same for all hydrocarbon fuels of present or foreseeable interest to the U.S. Air Force.
3. For flameholders of irregular shape it is found that any change in geometry which increases the surface to volume ratio of the wake region will have an adverse effect on flame stability.

Publications

The research led to the publications listed in references 3 to 6 below.

1. Ballal, D.R. and Lefebvre, A.H., "Weak Extinction Limits of Turbulent Flowing Mixtures," Trans. ASME, J. Eng. Power, Vol. 101, No. 3, pp. 343-348, 1979.
2. Ballal, D.R. and Lefebvre, A.H., "Weak Extinction Limits of Turbulent Heterogeneous Fuel/Air Mixtures," Trans. ASME, J. Eng. Power, Vol. 102, No. 2, pp. 416-421, 1980.
3. Ballal, D.R. and Lefebvre, A.H., "Some Fundamental Aspects of Flame Stabilization," Fifth International Symposium on Airbreathing Engines, pp. 48/1-8, 1981.
4. Rao, K.V.L. and Lefebvre, A.H., "Flame Blowoff Studies Using Large-Scale Flameholders," Trans. ASME, J. Eng. Power, Vol. 104, No. 4, pp. 853-857, 1982.
5. Rizk, N.K. and Lefebvre, A.H., "Influence of Laminar Flame Speed on the Blowoff Velocity of Bluff-Body Stabilized Flames," paper presented at the AIAA/ASME/SAE 19th Joint Propulsion Conference, Seattle, Washington, June 27-29, 1983. This paper is scheduled for publication in the AIAA Journal for Propulsion and Power, June 1986.
6. Stwalley, R. and Lefebvre, A.H., "Flame Stabilization of Large Flameholders of Irregular Shape," to be presented at AIAA 25th Aerospace Sciences Meeting, January 1987.

Awards

The paper "Flame Blowoff Studies Using Large-Scale Flameholders" received both the 1982 ASME Combustion and Fuels Award and the 1984 ASME Gas Turbine Award.

Task III

STABILIZATION OF VOID SPACE FIRES

S. N. B. Murthy

TASK III - SUMMARY

1. *Reporting Period:* 11-1

5. 5-81 through 3-31-86.

2. *Starting Date:* 11-15-81.

3. *Objectives:* The objectives are (i) the determination of (a) fluid dynamics of a cavity with external and internal flows and with an opening in a side wall and (b) ignition and flame stability of a fuel jet issuing out of a protrusion in a cross-flow of air and (ii) prediction of flowfields to determine the significance of mixture ratio and residence time distributions.

4. *Relevance:* The research is relevant to (a) aircraft void space fires and thus aircraft fire safety and (b) design of gas turbine and ramjet blocker-type injectors. Fundamental data pertaining to (a) secondary flow venting into a cavity flow from an external flow, (b) flowfield in the vicinity of variously shaped protrusions with different shapes and sizes of jets through them and (c) ignitability, flame stability and lean mixture ratio limits with respect to geometrical and flow characteristics have been generated.

5. *Principal Findings:* (i) Secondary flow into a cavity from an external flow can occur in the inward or the outward directions through an opening in the wall and, under certain conditions, in both directions simultaneously, but only with a vortex pattern in the opening. (ii) The Stronhal number corresponding to the occurrence of characteristic structures in the jet, entrainment of the jet material around the protrusion and mixing pattern depend upon geometry and flow parameters. (iii) Ignitable locations, lean limit of mixture ratio, flame stability and flame location depend upon generation of vorticity centers, shear layers and recirculation zones in relation to the protrusion and the jet. (iv) Predictions of inert and reactive flowfields confirm in a general fashion the experimental findings under (ii) and (iii) of the foregoing.

6. *Publications:* Three publications have been generated and are included in the list of References.

7. *Interactions:* Results of research and various aspects of unsolved problems have been discussed with the following: Fuels and Combustion and Aircraft Fire Safety branches of Wright-Patterson AFB; National Bureau of Standards; Boeing Airplane Co.; Sandia National Laboratories, Livermore, Applied Physics Laboratory, Johns Hopkins University; and NASA-Lewis Research and Ames Research Centers.

8. *Personnel:* In addition to three students, Professor (Emeritus) C. F. Warner participated in the project along with the Principal Investigator.

1. INTRODUCTION

Two topics of research have received attention under the project, namely:

- (1) Secondary flow into a cavity from an external flow when there is an opening in the side wall of the cavity, as a function of velocity and pressure ratio.
- (2) Ignition and flame stability characteristics of a jet of gaseous fuel through a protrusion, issuing into a cross-stream of air.

The major effort has been devoted to topic (2).

1.1. Relevance of Research

Topic (1) is of interest wherever there is a secondary flow into a cavity flow from an external flow. In particular, external and internal flows with small differences in pressure and in velocity are of interest in aircraft void space fires. The topic is also of relevance in the design of gas turbine combustor walls.

Topic (2) is of interest in aircraft void space fires, ignition, flame stability and flame propagation characteristics. It is also of relevance in the design of blocker-type fuel injectors for gas turbines and certain ramjet configurations.

A variety of investigations have been reported in the literature on jets in cross-flows, but they relate to jets issuing directly out of a boundary wall. One method of controlling the entrainment and then mixing of a jet in cross-flow is to utilize a protrusion located over a wall for issuing the jet. Both the geometry of the protrusion and that of the jet become parameters that can be selected to obtain desired flow interactions. The flow interactions determine the distribution of residence time and mixture ratio in relation to the protrusion and the jet.

1.2. Outline of Report

Section 2 provides a description of the test rig. The investigation on secondary flow into a cavity flow from an external flow (Topic 1) is described in Section 3. The investigation on ignition and flame stability (Topic 2) is described in Section 4. A discussion of results is presented in Section 5.

2. TEST RIG

Two test rigs have been assembled as follows:

- (i) Test rig for cold flow studies; and
- (ii) Test rig for combustion studies.

2.1. Test Rig for Cold Studies

A schematic of the test rig is provided in Fig. 2.1. The test cavity (1) is built with transparent plexiglass sheets. The adjoining cavity (2) with the free stream flow is also shown in the figure. The speed and pressure of airflow can be adjusted in (1) and (2); the velocity can be varied in the range of 10-25 mps in (1) and 20-100 mps in (2), and the pressure difference between (1) and (2), 0.5-1.2 psi. Cavity (1) is the actual test section and (2) represents the "surrounding" or "adjoining external" flow. Figure 2.1 also indicates the gravitational action direction, noting that gravity is a consideration in low speed combustions flows.

The test rig has been utilized for (a) flow visualization and (b) measurement of overall flow quantities.

In cavity (1), the test section, a variety of protrusions can be incorporated as well as various shapes of walls for attaching the protrusions. These are illustrated in Fig. 2.2.

By mixing smoke into the low speed jet flow, one can study the jet mixing and spreading characteristics.

2.2. Test Rig for Combustion Studies

The test rig is essentially the same as illustrated in Fig. 2.1. Modifications have been made by (a) replacing (1) and (2) with stainless steel and steel bodies, respectively, (b) providing methane gas injection into the test section (1), (c) introducing an ignitor, and (d) locating quartz windows for optical observation.

Other instrumentation and diagnostics are being examined.

The ignitor design is shown in Fig. 2.3. It can be observed that the source of ignition can be moved both radially and circumferentially in relation to the jet through the protrusion and the gravitational direction.

2.3. Preliminary Tests

The cavity flow was measured and adjustments made to the apparatus to ensure that (a) the flow velocity was uniform over each part of the test section flow to within one per cent of the mean flow and (b) the turbulence intensity in the air streams was under 2.0 per cent.

The momentum boundary layer thickness over the wall with the protrusion was measured and found to vary between 1.5 and 2.0 mm. It was possible to reduce the boundary layer thickness to 0.5 mm. in selected tests. It may be pointed out that the smallest height of any protrusion tested was 3.0 mm.

3. SECONDARY FLOW INTO CAVITY

The parameters varied during the tests were: static pressure and velocity of cavity flow; static pressure and velocity of external flow; and diameter of the circular opening in the side wall.

3.1. Results

The secondary flow into the cavity as defined in terms of a parameter, called the flow parameter, defined as follows.

$$\text{FlowParameter} = \dot{m} / [A \rho_1 I^{1/2}] \quad (3.1)$$

where in, A and ρ_1 represent the mass flow entering the cavity, the area of cross-section of the opening and the density of the cavity fluid, respectively. I represents what is called the pressure difference parameter, defined as follows.

$$I = 1 + \Delta P_{12} / q_1 \quad (3.2)$$

where ΔP_{12} is the difference in pressure between the cavity and the external fluids and q_1 , the dynamic head in the cavity.

Experimental results obtained over a range of flow velocities, pressures and size of openings are presented in Fig. 3.1 in terms of mass flow parameter as a function of pressure difference parameter.

Several regimes of flow were found to exist depending upon the relations between V_1 , V_2 , and V_{ref} , (\cdot)₁, (\cdot)₂ and (\cdot)_{ref} denoting the cavity flow, the external flow and flow through the opening, respectively. The latter was defined as $[\Delta P_{12} / \rho]^{1/2}$ where ρ was the mean value of density across the opening. In particular, three regimes were recognized as follows.

Regime 1: $V_1 > V_{ref}$ and $> V_2$;

Regime 2: $V_2 < V_{ref}$ and $> V_2$;

Regime 3: $V_1 < V_{ref}$ and $< V_2$.

It was found that

- (i) there was a vortex formation at the opening in regime 2;
- (ii) the flow was bidirectional in regime 2;
- (iii) the flow was nonsteady in regimes 2 and 3; and
- (iv) the flow reduced in regime 2 compared to regimes for the same pressure difference and area of cross-section of opening.

Although no extensive measurements were made to determine the influence of the height of the opening, equal to the thickness of the wall with the opening, it was found that regimes 2 and 3 were affected by an increase in thickness of the wall, especially the unsteadiness of the flow.

4. IGNITION AND FLAME STABILITY OF FUEL JET THROUGH PROTRUSION IN CROSS-FLOW

The investigations consisted of the following:

- (1) Flow visualization;
- (2) Ignitability of gaseous fuel jet;
- (3) Flame structure;
- (4) Lean limit for ignition; and
- (5) Prediction of inert and reactive flowfields.

The parameters varied were as follows:

- (1) Geometry of protrusion in terms of height, shape, and orientation, when relevant, and cross-sectional dimension;
- (2) Geometry of jet given by the diameter of the jet and its relation to the cross-sectional dimension of the protrusion;
- (3) Air and fuel velocities; and
- (4) Wall (momentum) boundary layer.

The fuel gas utilized was propane or methane, the latter principally when determining lean ignition limits. The highest purity, commercial grade fuel was utilized.

4.1. Flow Visualization

The flow visualization studies were divided into the following.

- (1) Visualization of flow over the wall with the protrusion;
- (2) Visualization of flow pattern around the protrusion by injection of smoke; and
- (3) Visualization of jet flow utilizing smoke as a tracer.

The smoke was generated utilizing a smoke generator operated with fog juice. Utilizing ordinary light, observations were made with the naked eye and then recorded with a still and a Dyntax camera, the exposure times being about one microsecond and the moving pictures taken at a rate of, up to, 20,000 frames per second.

Various aspects of results obtained are presented in Ref. 3.1, which has been included in Appendix III.1. to this Report.

4.2. Ignitability of Gaseous Fuel Jet

Ignitability of the fuel-air mixture at any location was defined as the ability to ignite a mixture when the ignitor was held, with ignition energy on, for a period of 60-100 seconds and to obtain a stable flame when the ignitor was turned off.

In each experiment, with a given protrusion, air flow and fuel gas flow, the ignitor located at a particular radial distance from the axis of the fuel jet was traversed circumferentially and height-wise to determine all of the locations at which ignition was possible according to the criterion mentioned in the preceding para. The ignitor was then moved to the other radial location and the series of trials was repeated.

The experiments were carried out with a number of protrusions of various shapes and heights, set in different orientations when meaningful. A photograph of various protrusions examined is presented in Fig. 4.1.

The results obtained in a few selected cases are summarized in Ref. 3.3, attached in Appendix III.1 of this Report.

4.3. Flame Structure

The location and shape of the flame were obtained in each of the cases where the flame was stable according to the criterion employed in Section 4.2., utilizing high speed photography. The shortest photographic film exposure time utilized was one millisecc. In each case, at least two views of the flame were photographed, one along the axis of the jet and the other in the plane containing the axis and the cross-flow direction.

The objective in obtaining the photographs was to determine, at least on a semi-integrated basis, the location and shape of the flame in relation to protrusion geometry, air and fuel flow parameters and fuel jet.

A number of pictures obtained in selected cases are provided in Ref. 3.3, included in Appendix III.1 to this Report.

4.4. Lean Limit for Ignition

In continuation of experiments on ignitability discussed in Section 4.2, experiments were performed in each case to establish the lowest fuel-air mixture ratio at which the flame was stable. It will be recalled that flame stability was part of the criterion for ignition. In the subsequent experiments, the fuel flow rate was reduced, while keeping the air flow rate constant, until the flame was just unstable or extinguished and the lean mixture ratio was noted as a limiting value. It is obvious that this limit is not related to ignition location and is strictly a flame stability limit related to mixture ratio and residence time.

Experiments were performed with both propane and methane gas. Differences were observed both with respect to locations at which ignition was possible, ignition energy required and lean mixture limit. Generally methane was more difficult to ignite, requiring both increased methane flow rate and also larger ignition energy.

Results of observations in selected cases are presented in Ref. 3.3., attached in Appendix III.1 to this Report.

4.5. Predictions

The objective in obtaining predictions of the flowfield was to obtain the distribution of velocities and the distribution of concentration of fuel around the protrusion and then determine, under the fast chemistry assumption, the heat released by chemical reaction. Calculations were performed both under inert and reactive flow cases. Although it was found that inclusion of turbulence parameters did not affect the flowfield substantially, a standard (k, ϵ) type of model was included in all of the predictions. The reaction between propane and air was considered on the basis of one-step, equilibrium, fast chemistry.

The predictions were performed utilizing a modified version of the so-called PHOENICS code, developed originally by CHAM, Ltd., of the U.K., and distributed by CHAM, Ltd. of America. The code provides a means of performing three-dimensional, turbulent, chemically reactive flowfield calculations. In the current calculations, the code was utilized

in a semi-parabolic formulation with specified wall functions. A variety of grid distributions was tried, although entirely on an ad hoc basis, and it was found that the use of approximately 20,000 nodes distributed in the three orthogonal directions and about 200 iterations was adequate to obtain adequate convergence of results and recognizable patterns of flow.

Predictions of inert and reactive flows performed in a number of cases have been presented in Refs. 3.1-3.3, all of them included in Appendix III.1 to this Report.

5. SUMMARY AND CONCLUSIONS

The two major aspects of the investigations are (i) Fluid dynamics of flow into a cavity, through an opening in a side wall, from external flow and (ii) ignition and flame stability of a fuel jet through a protrusion in a wall with a cross-flow of air.

5.1. *Fluid Dynamics of Flow into Cavity Through an Opening in a Side Wall from an External Flow*

- (i) Three regimes of flow are possible: (a) pressure driven flow into the cavity from the external flow; (b) flow that is bidirectional, being spatially and temporarily reversing in direction; and (c) flow with a slight ejector action due to difference in velocity between the external and the cavity flows.
- (ii) During bidirectional flow there usually is formed a vortex at the opening in the side wall. The unsteadiness in the flow may be associated with the formation of such a vortex.

5.2. *Ignition and Stability of Fuel Jet Through Protrusion in Cross-Flow*

Several observations may be made based on data obtained in preliminary studies.

- (i) The flowfield in a rectangular region of dimensions 8x4x4 units of protrusion cross-sectional size is fully three-dimensional with several singularities, recirculation zones and concentrated regions of vorticity. It appears that no closed streamlines exist, although this observation is based on "integrated" planar viewing and recording of flow.
- (ii) The observations from surface paint photography of the cavity wall with protrusion illustrate the nature of singularities occurring both upstream and downstream of the flow. However, it would be incorrect to discern from such pictures the distribution of shear stress since simple topological considerations cannot be directly applied in such flows¹¹.
- (iii) The observations from surface paint photography of the top surface of the protrusion show the influence of the ratio of the jet diameter to the cross-sectional size of the protrusion. It appears that there is a critical range of the ratio within which the surface includes upstream low pressure regions with strong vorticity concentration. In photographs of smoke trace through a jet of, for example, 6.0 mm. issuing out of a cylindrical or cubic protrusion of cross-section equal to 12.0 mm., it is found that the jet spreads upstream over the surface and there is some entrainment of the jet upstream of the protrusion. When the jet size is about 3.0 mm., no such upstream effects arise.

- (iv) The observations from photographs with smoke injection (through a hole of 0.01 cm. located at about mid-height of a 12.0 cm. protrusion) into the upstream region of the protrusion show the formation of vortices related to the stagnation of the flow, at least one of them clockwise towards the wall and a second counter-clockwise away from the wall. No further discrimination has become feasible and one can only conclude that strong interactions are likely to occur between such vortices, flow pattern generated over the protrusion top surface and the jet.
- (v) The flow pattern over the protrusion surface (the two side walls in the case of a cuboid and the cylindrical surface in the case of a circular cylinder) is a function of (a) the local wall boundary layer thickness in relation to the height of the protrusion and (b) the orientation of the protrusion with respect to the streamwise direction in the case of bodies with corners. The influence of secondary flow generated by a corner on the main stream is very significant in the entrainment (of all but small jets) around the protrusion.
- (vi) Finally, an attempt was made utilizing a stroboscope to establish a relation between the observed periodicity in vortex structures and the geometrical and low parameters. It may be pointed out that the frequency obtained with a protrusion of large height corresponds more nearly to that of a simple jet in cross-flow. The effect of jet diameter on frequency is not clear.

The ignition and flame stability characteristics of a jet through a protrusion in cross-flow depend in a complex fashion upon the flowfield interactions. It is often of interest in the case of two-dimensional flameholders to determine an equivalent aerodynamic body to analyze flame stabilization. A three-dimensional blocker cannot be treated on such a simple basis. The cross-sectional dimensions of the protrusion and the jet and the height of protrusion can be utilized, however, as parameters for controlling ignition and flame stability for given jet and cross-flow velocities.

The overall test program was based on 120 combinations of a variety of parameters in each series of tests: (i) protrusion cross-section and height, (ii) jet cross-section, (iii) cross-flow and jet velocities (iv) gaseous fuel composition. Similarly, a large number of cases was predicted.

The flow visualization pictures demonstrate the strong role of vortex flow generated by the protrusions in determining flame structure, intensity and location. At given jet and cross-flow velocities substantial differences can be observed both in the flow at the boundary wall and in flame development for the three cases of cylindrical and side-oriented and corner-oriented square protrusions. A reduction in cross-flow velocity by an order of magnitude introduces substantial changes in the flow and combustion characteristics; no simple similarity rules can be constructed.

The ignition characteristics for three protrusions are also not governed by simple similarity considerations. It has been found that there are specific locations where ignition is feasible for given geometry and flow conditions, the locations varying three-dimensionally relative to the protrusion.

A number of limits to ignitability and flame stability were found with respect to the shape and height of a protrusion and the size of the jet. The cylindrical protrusion was found to give the "best" ignition and flame stability compared with the square protrusion in

either orientation. The "best" designation refers to the number of concentrations of jet diameter and ignitor location at which ignition and stable flame were possible. In the case of the square protrusion, the side-oriented configuration proved "better" than the corner-oriented configuration. Whereas the case of side-oriented protrusion, some entrainment of jet material was found, upstream of the protrusion with jets of diameter larger than half corner-oriented protrusion. Below a minimum height of protrusion it was not possible to ignite the fuel whatever the cross-section of the protrusion and the jet and also the flow velocities. Similarly, below a minimum jet diameter, ignition was not possible in all cases.

The manner in which the flame becomes stabilized by the protrusion, when there is flame stability, is not necessarily by attachment to the protrusion. The flame in fact may be detached from the protrusion. Such detachment indicates the existence of vortex centers or stagnation regions in the vicinity of the protrusion that can act as flame holders, while the region between such centers and the protrusion does not have the required composition or residence time to extend the flame to the surface of the protrusion. It was found in such cases that the protrusion remained cold even after several minutes of combustion, although it should be pointed out that the protrusion carried a cold jet of fuel through it.

The predicted velocity distributions are qualitatively acceptable downstream of the protrusion but do not reveal the details of flow ahead of the protrusion, that can be observed in flow visualization. In view of the interactive nature of velocity and concentration distributions, predicted concentration distributions and enthalpy generation in reactive flow cases are subject to the same limitation.

The principal observations from predictions are as follows.

- (i) The overall flowfield, including formation of main recirculation distribution and reaction zone shape and location, is predicted by the PHOENICS code as adapted and used here. The predictions are adequate to examine the ignitability of the fuel jet and the stability of flame, based on residence time and mixture ratio considerations.
- (ii) The major features of flow interactions do not seem to depend upon turbulence very greatly although the investigation was limited in examining turbulence modelling. Even such features as entrainment of the jet material into upstream sections seem to depend primarily on mean flow interactions.
- (iii) Details concerning jet structure of flowfield development in the near field region of the protrusion are poorly recovered. While substantial advances have been made as in Refs. 6 and 8 in those regards, it is not expected that the current formulation can yield three dimensional critical flowfield conditions. From the point of view of design of protrusion/jet shape and height/width, even the influence of corners can be established in the predictions, but not the complete details in the vicinity of corners. At the same time, the distribution of u and w components at $y=0$ plane do indicate at least the location of the horseshoe vortex and the reverse flow regions enclosed by it.

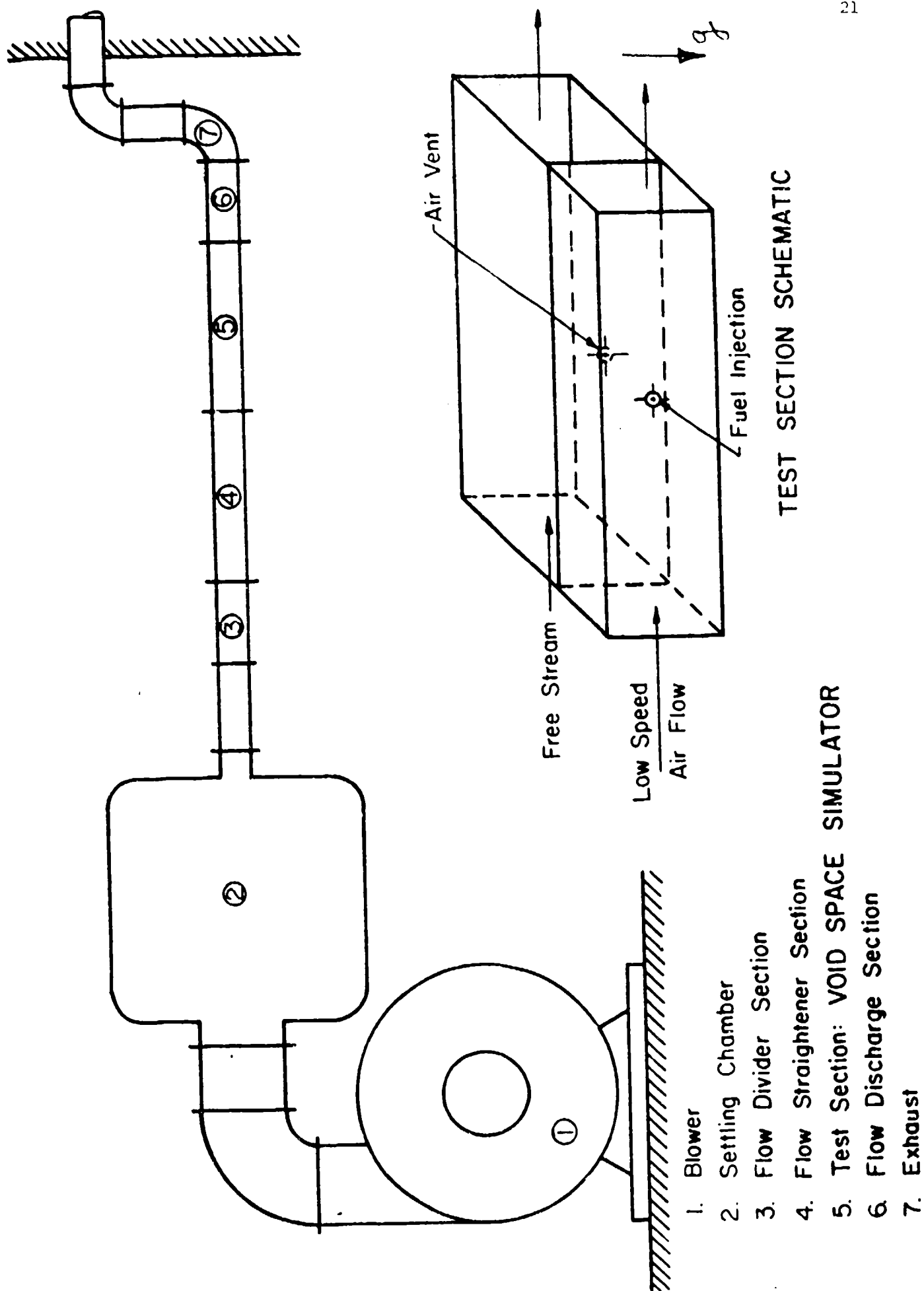
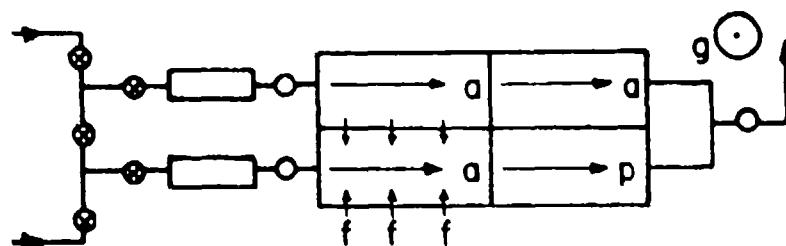
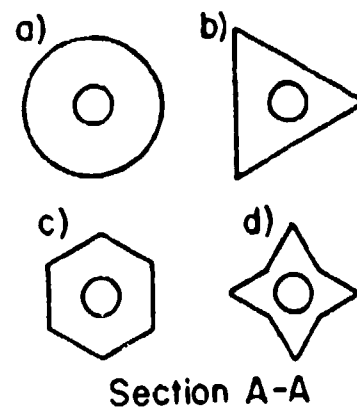
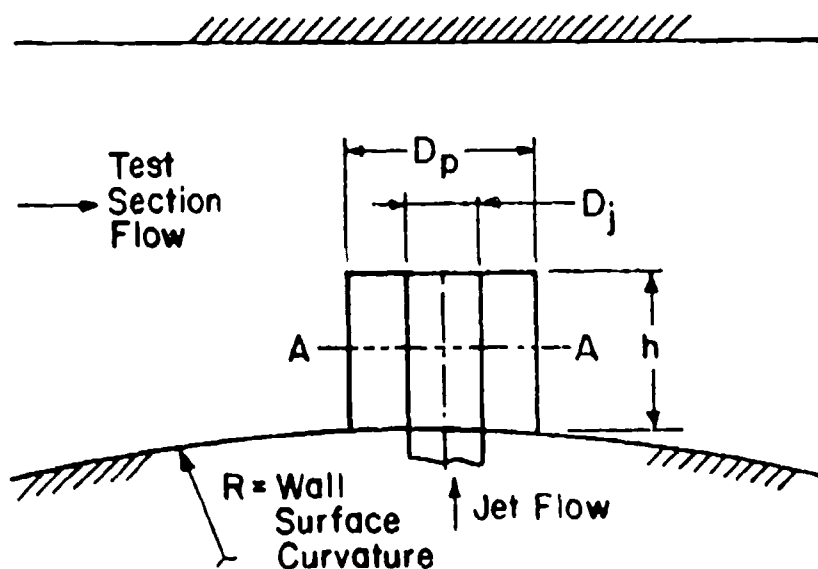


Fig. 2.1. VOID SPACE SIMULATOR TUNNEL

EXPERIMENTAL CONFIGURATION



- TEST SECTION: 15×10×60 cms
- FREE AIR FLOW VELOCITY:
20-100 m/s
- a DENOTES AIR
f DENOTES FUEL
p DENOTES PRODUCT

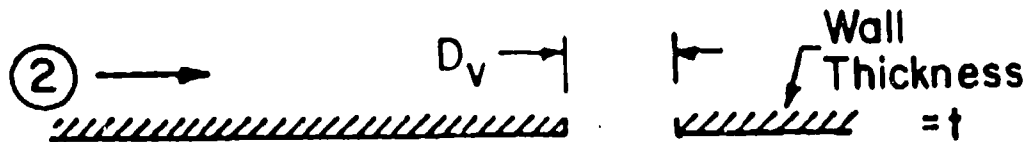


PARAMETER	RANGE
D_p	0.5 in.
h	0.125-0.5 in.
D_j/D_p	0.125-0.75
R	∞ , + and -
V_i	10-50 fps
$Re_{L=1ft}$	$50-250 \times 10^3$

Fig. 2.2.

FLOW THROUGH AIR VENT

● PARAMETERS



① → VOID SPACE FLOW



● REGIMES WITH $\Delta P_{O12} > 0$

$$\Delta P_{O12} = P_{O1} - P_2 ; \Delta P_{12} = P_1 - P_2$$

1. $V_1 > V(\Delta P_{12} / 2\rho)$ and $> V_2$
2. $V_1 < \quad \quad \quad$ and $> V_2$
3. $V_1 < \quad \quad \quad$ and $< V_2$

● CONCLUSIONS

1. VORTEX FORMATION IN CASE 2
2. FLOW BIDIRECTIONAL IN CASE 2
3. FLOW NONSTEADY IN CASES 2 & 3
4. FLOW REDUCED IN CASE 3

COMPARED TO CASE 1

— BASED ON CONSTANT D & D/t

FIG. 3.1 FLOW THROUGH AIR VENT: PARAMETERS

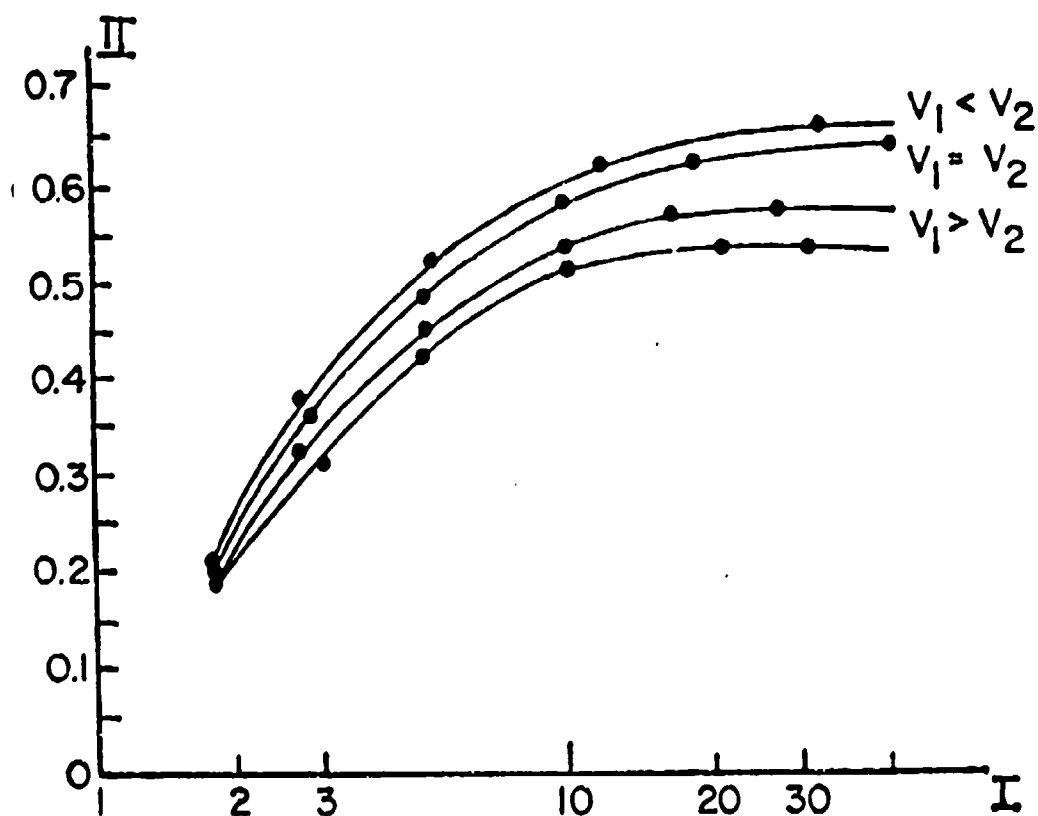
FLOW THROUGH AIR VENT (CONTINUED)

• RANGES OF PARAMETERS

$D \sim 0.25 - 0.50$ in.

$\Delta P_{12} \sim 0.5 - 1.50$ psi

$V_1, V_2 \sim 30 - 75$ fpm



$$I \equiv [1 + \Delta P_{12} / q_1] ; \quad II \equiv \dot{m} / [A \cdot \rho_1 \cdot I^{1/2}]$$

FIG. 3.2 CORRELATIONS OF FLOW THROUGH VENT

REFERENCES

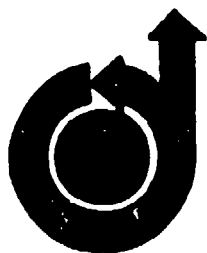
- 3.1. Hong, S. K., Murthy, S. N. B., and Warner, C. F., "Jet Through a Wall Protrusion in Cross-Flow," *AIAA*, 84-1167, 1984.
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- 3.3. Murthy, S. N. B., Warner, C. F., and Yan, J., "Ignition and Flame Stability of Fuel Jet Through Blockers in Cross-Flow," *AIAA*, 86-1535, 1986.

Appendix III-1.

AIAA-84-1167

**Jet Through a Wall Protrusion
in a Cross-Flow**

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AIAA/SAE/ASME
20th Joint Propulsion Conference
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Reactive Jet Flows through Protrusions in Cross-Flow

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Abstract

A simple method of affecting a reactive jet in cross-flow is to introduce the jet through a wall protrusion of chosen shape and height. The resulting flowfield, including structure of the jet, entrainment into it, its spread and reattachment/dispersion, reaction zone geometry and enthalpy release, depends upon the interaction between the jet and the wake of the finite height protrusion. Based on physical observations of the flowfield, a model has been developed for the turbulent reactive flowfield. Numerical predictions of the flowfield obtained with a semi-parabolic, finite difference solution procedure applied to turbulent three-dimensional flow equations illustrate the nature of overall interactions.

1. Introduction

The gaseous jet in a cross-flow has been and continues to be a subject for investigation (Refs. 1-6) in many contexts; combustion in engines and in furnaces is one such context and adds further complexities to the interactions. Three problems of interest even in a gas jet discharging into a gaseous crossflow are (i) the mean flowfield of the jet, its penetration and spread and its eventual dissipation or reattachment on the boundary wall, (ii) the mean flowfield around the jet including the horseshoe vortex and wake, and (iii) the structural features of the jet, the large and small scale structures within the jet, that are responsible for entrainment and hence the mixing of the jet. The flow interactions between the jet and the cross-flow invariably involve turbulence. Figure 1 is a schematic representation of the flowfield, following Ref. 3.

The flow interactions are governed by (a) the Reynolds number and the boundary layer features of the cross-flow, (b) the ratio of jet momentum to the cross-flow momentum, (c) the geometry of the jet, (d) the turbulence characteristics of the two flows and (e) the state and molecular properties. Attention is restricted here to cold flows with little difference in temperature or pressure, although the composition of the two flows may be different; for example, cross-flow of air and a jet of gaseous fuel such as methane or propane.

Modifications to the flow interactions in a jet in cross-flow configuration can be introduced through three types of geometrical changes. (i) shape of boundary wall in the vicinity of the jet, (ii) jet shape and exit conditions and (iii) introducing a wall protrusion through which the jet issues. The latter provides opportunities for controlling various features of flow interactions through (a) selection of the location at which the jet is injected into the cross-flow and (b) obtaining various flowfields around the protrusions of different shapes and hence modification of interaction of the jet flow.

Jet through a wall protrusion in cross-flow then provides the following additional parameters

compared to the case of a simple round jet in a cross-flow past a flat plate: protrusion geometry, ratio of jet cross-section to a relevant cross-sectional dimension of the protrusion and height of protrusion in relation to the thickness of the wall boundary layer. Attention is again restricted here to protrusions of height equal to one or more times larger than the wall boundary layer thickness.

Two typical protrusion cross-sections of interest are the circle and the square, shown in Fig. 2(a). The square protrusion provides an opportunity for two major orientations with respect to the oncoming flow. Figure 2 provides a schematic of a laboratory test set-up for the flow under consideration.

1.1. Relevance. The problem of jet through a wall protrusion in cross-flow is of interest in a number of problems of fuel jet ignition, flame stability and flame propagation in gas turbine and ramjet combustors with "blockers" and also in fuel tank fires following rupture of tank skin by external impact. Some aspects of such relevance can be found in Ref. 7.

1.2. Outline. In Section 2 a brief discussion is presented of certain experimental observations made in the test set-up illustrated in Fig. 2. We are principally concerned with the prediction of such flowfields. A scheme for flowfield predictions including chemical reactivity between oxidant (air) and fuel (methane gas) is presented in Section 3. The results may be interpreted in relation to mixture ratio and residence time of mixture that result from connectedness of the entire flowfield including vorticity centers.

2. Experimental Observations

The preliminary experimental studies were divided into three parts: (i) flow past protrusions, (ii) flow interactions between jet and cross-flow and (iii) combustion experiments with an ignitor that could be traversed circumferentially and radially around the protrusion. It may be pointed out that the test cavity was supplied with air at near-atmospheric pressure, the velocity of flow ranging over 5-30 m/sec. The protrusion cross-sectional dimension was 12.5 mm. with jets of diameter equal to 3.15, 6.30 and 9.50 mm. in different cases. The height of the protrusion was varied over the range of 0-12.5 mm. The Reynolds numbers based on cavity dimensions, protrusion height and jet diameter are of the order of 1×10^5 , 1×10^4 and 1×10^3 , respectively, in a typical case. In combustion experiments, the jet material was methane or propane gas. A small ignitor of 0.5 mm. dia. was traversed around the protrusion, the circumferential location (relative to the mean cross-flow direction), the radial location (with respect to the axis of the jet) and height (relative to the height of the protrusion) being adjusted parametrically (Fig. 2(c)).

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**Ignition and Flame Stability of Fuel
Jet Through Blockers in Cross Flow**

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